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A PERFORMANCE EVALUATION OF ELEVATION DATABASE INTEGRITY MONITORS FOR SYNTHETIC VISION SYSTEMS

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Abstract

Key words: integrity monitoring, terrain elevation database

Terrain elevation databases or digital elevation models (DEMs) are used for a wide variety of applications such as surveillance, surveying, mission planning, and environmental planning. This paper focuses on the application of DEMs in Synthetic Vision Systems (SVS). SVS are intended to provide pilots with an advanced display that depicts terrain information as well as other information about the external environment such as obstacles and traffic. When utilizing terrain elevation databases in applications that require higher levels of integrity than an advisory system, it is required to include an integrity monitor that guarantees the specified probability of false alarm (fault-free detection), probability of missed detection, and time-to-alarm. The terrain information displayed to the pilot is synthesized from DEMs. The DEMs in use today are often generated by many different technological sources (remote sensing, photogrammetry, etc.) and pieced together by humans. Several approaches to DEM integrity monitoring are discussed and compared. One of the methods is based on the comparison of the DEM with downward-looking (DWL) sensor information. Flight test results with a real-time prototype DWL integrity monitor are shown.

Introduction

Synthetic Vision Systems (SVS) are intended to provide pilots with an advanced display that depicts terrain information as well as other information about the external environment such as obstacles and traffic. Display of synthetic terrain information to the pilot on either a head up display (HUD) or head down display (HDD) has the potential to improve the flight safety by reducing the likelihood of Controlled Flight Into Terrain (CFIT). NASA's aviation safety program is investigating SVS as an enabling technology for a wide variety of applications such as reduction of Controlled Flight Into Terrain (CFIT), low-visibility surface operations, advanced precision approach procedures, and low-visibility loss-of-control scenarios. This range of applications is discussed in NASA's "Concept of Operations for Commercial and Business Aircraft Synthetic Vision Systems" [1]. The focus in this paper is the use of SVS for CFIT-reduction. To mitigate CFIT, several strategies have been, and are being, pursued by the government and private sectors, such as Terrain Awareness and Warning Systems (TAWS). TAWS is currently being mandated by the FAA for use on all turbine-powered U.S.-registered airplanes type certified to have six or more passenger seats [2]. It is important to note that TAWS is purely an advisory system.

When utilizing terrain elevation databases in applications that require higher levels of integrity than advisory systems, it is required to include an integrity monitor that guarantees the specified probability of false alarm (fault-free detection), probability of missed detection, and time-to-alarm. Examples of applications that require critical levels of integrity would be (tactical) low visibility navigation near the airport. Examples of applications that require essential levels of integrity would be near-term planning in low visibility.

Integrity monitoring of elevation database information is accomplished by a consistency check between the information stored in the databases and the information derived from external sensors. Based on the sensor technology that is being used to monitor the system's integrity, two categories of integrity monitors are discussed:

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integrity monitors based on downward looking (DWL) sensor information and integrity monitors based on forward looking (FWL) sensor information. This paper discusses and compares approaches to DEM integrity monitoring and shows flight test results from a prototype SVS with DWL-based integrity monitor. Sensitivity of the methods to spatial resolution, terrain database accuracy, and sensor specification will be addressed.

It is important to note that the proposed systems are neither meant as a navigation aid nor as a terrain awareness and warning system; The proposed systems is a subsystem of an SVS [3] for the sole purpose of monitoring the quality of the terrain data input to the advanced cockpit displays.

1. Terrain database properties and characteristics

Terrain elevation databases stored digitally and defined at discrete spatial points (posts) are often referred to as digital elevation models or DEMs. A variety of sources provide DEMs specified by a number of parameters, such as the post-spacing or spatial resolution, the horizontal and vertical references or datums, and the circular and linear errors. The circular error probability (CEP) represents the horizontal accuracy specification on the post-position, whereas the linear error probability (LEP) or vertical error specifies the accuracy in the vertical direction (height). Table 1 shows the parameters for a variety of available DEMs.

	Post Spacing	CEP	LEP	Horizontal Datum	Vertical Datum	Segment Size
DTED 0	30 arc-sec	See below	See below	WGS84	MSL	1^o x 1^o
DTED 1	3 arc-sec	<50m, 90%	<30m, 90%	WGS84	MSL	1^o x 1^o
USGS	3 arc-sec (v)	N/A	N/A	WGS84	NGVD27	1^o x 1^o (v)
ASM100	15 arc-sec	<50m, 90%	(*)	WGS84	MSL	100 nmi x 100 nmi
ASM12	6 arc-sec	<50m, 90%	(*)	WGS84	MSL	12 nmi x 12 nmi
NGS5	5 m	1m, 90%	1m, 90%	WGS84	MSL	8.8 nmi x 3 nmi

Table 1. Digital Elevation Models (DEMs)

Various DEMs were available for the Asheville, NC and Athens, OH areas to support the flight-test analyses and real-time implementation. The DEMs used in this paper are the Digital Elevation Terrain Data (DTED) levels 0 and 1 provided by the National Imaging & Mapping Agency (NIMA), the Airport Safety Modeling Data (ASM100 and ASM12), and a USGS DEM. The ASM100 and ASM12 elevation databases are derived from DTED level 1 elevation data; The elevation for each of the posts was defined as the maximum height of all surrounding posts in the DTED level 1. The ASM data sets are publicly available from NOAA for terrain-impacted airports. For the geographic areas of interest the DTED level 0 and level 1 databases have a similar horizontal and vertical accuracy specification: CEP < 50m, 90% ($?_{hor}$ = 30.4 m), LEP < 30m, 90% ($?_{ver}$ = 18.2 m). The major difference between DTED Level 0 and 1 lies in their spatial resolutions; whereas DTED level 1 has a post-spacing of 3 arc-seconds, DTED level 0 has a post-spacing of 30 arc-seconds.

Spatial resolution is an important characteristic of the DEMs; A limited spatial resolution may result in significant interpolation errors because the terrain may be under-sampled. Another interpolation aspect concerns the definition of CEP and LEP: they are defined at the post locations and not necessarily in between the posts. This may result in an actual error variance that exceeds the specified or nominal error variance when interpolating in between post locations. In geographic areas with a large terrain standard deviation ("rough" terrain), large interpolation errors may be expected. [5] identifies the standard deviation of the terrain elevation samples, $?_T$ as a measure of terrain "roughness". The ratio between $?_T$ and the vertical noise on the elevation samples, $?_N$, is an indicator for how well the elevation samples can be used for matching a set of elevation measurements to the database elevation samples; a smaller ratio requires a larger set of elevation measurements and visa versa. The value for $?_N$ depends on the specified CEP and LEP. Three categories of terrain were identified: (1) regions with $?_T$ < 30 are considered to be smooth; (2) regions with $?_T$ > 300 ft are considered to be mountainous; and (3) regions with 30 < $?_T$ < 300 to appear be hilly. In areas with a higher value for $?_T$, the interpolation error effect of a limited resolution is larger also. However, it is in these geographic areas that misleading terrain information is most likely to be hazardous. The effects of the limited resolution and their impact on the nominal performance will be illustrated in the flight test result section of this paper. The Asheville, NC region has a terrain roughness equal to $?_T$ = 1,010ft and is thus considered mountainous, whereas the Athens, OH region has a roughness equal to ? $_T$ = 145 ft and is therefore considered hilly.

The Shuttle Topography Mission, which was flown in January 2000, will provide us with another DEM. This Shuttle mission mapped the surface of the Earth between plus and minus 60 degrees latitude (approximately). The main advantage of this DEM will be the fact that the characteristics (errors) should be consistent across the DEM as it comes from a single source. Other "world-wide" DEMs historically come from multiple sources and are "patched" together.

2. Real-time terrain database integrity monitoring

Integrity monitoring of DEM information is accomplished by a consistency check between the information stored in the databases and the information derived from external sensors. Based on the sensor technology that is being used to monitor the DEM integrity, three categories of integrity monitors can be considered: (1) integrity monitors based on downward looking (DWL) sensor information; (2) integrity monitors based on forward looking (FWL) sensor information; and (3) integrity monitors based on both DWL and FWL sensor information.

2.1 Integrity monitoring based on downward- looking sensor technology

In the proposed downward looking integrity scheme sensor information from a Differential Global Positioning System (DGPS) and radar altimeter are used to generate a synthesized, or "sensed", elevation profile (see figure 1). This profile is compared to the elevation profile stored in the database server and if there are inconsistencies between the two profiles, an integrity alarm will be generated and presented to the pilot in some fashion. Examples of DGPS that may be utilized are the Wide Area Augmentation System (WAAS) or Local Area Augmentation Systems (LAAS). The difference between the synthesized and database profiles is referred to as the absolute disparity, whereas the difference between two successive absolute disparities is referred as the successive disparities. Based on the underlying and/or specified error characteristics of the sensors and the databases, probability density functions can be derived for the absolute and successive disparities. Test statistics such as the mean square difference, the mean absolute difference, and the cross-correlation, are derived from these metrics and statistically assessed to obtain integrity thresholds. These thresholds are derived under the fault-free condition and based on the probability of false alarm. Minimum detectable biases are computed under the faulted condition from the probability of missed detection and calculated threshold values.

Techniques similar to the one proposed for terrain database integrity monitoring have been used for terrain-based navigation. Examples are Terrain Contour Matching (TERCOM) [5,6], the Sandia Inertial Terrain-aided Navigation (SITAN) [5,6], and Terrain Profile Matching, TERPROM [6]. These systems utilize a radar altimeter combined with another positioning source to derive synthesized terrain elevations. Correlation of the synthesized terrain elevations with the DEM elevation samples will enable position "fixing". It is important to note that these systems were designed to enable position "fixing" in support of autonomous navigation, not as integrity monitors for a display suite such as SVS. It is furthermore important to note that for regions with relatively small values of ? $_T$ the correlation time must be increased significantly to achieve the same performance levels.

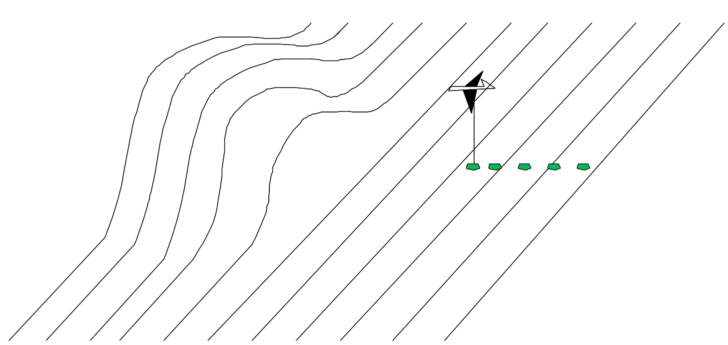

Figure 1. Downward-Looking sensor based DEM integrity monitor

The synthesized elevation measurements are obtained by subtracting the height above ground level measured by the radar altimeter from the altitude above mean sea level computed by the Differential Global Positioning System (DGPS). The radar altimeter measures the height above ground level (AGL) of the radar altimeter receiving antenna (mounted on the bottom of the aircraft). However, it is important to realize that the radar altimeter measurement accuracy is a function of the altitude and the rate at which the altitude changes. Furthermore, banking of the aircraft may cause the radar altimeter beam to measure a “slant-range” instead of a “plumb bob” range [7].

The test statistic, *T*, used for the integrity monitor is given by the mean square difference (MSD) of *N* consecutive absolute disparities, or:

$$T \; ? \; \frac{N}{?_p^2} MSD_{AD} \; ? \; \frac{1}{?_p^2} \overset{N}{\underset{i?1}{?}} p^2(t_i) \qquad (1)$$

where $p(t_i)$ is the absolute disparity:

$$p(t_i) \; ? \; h_{SYNT}(t_i) \; ? \; h_{DTED}(t_i) \qquad (2)$$

h_{SYNT} is the synthesized height and h_{DTED} is the height as derived from the DEM. Both elevations are defined at time t_i. Ideally, the difference between the stored and synthesized elevation would be zero. However, nominal errors in the sensor performance and stored entries in the DEM cause the absolute disparity to have a nominal error distribution [8]. Overbounding the bias and random error components of both the sensor and the DEM yields a probability density function (PDF) for the absolute disparity under the fault-free condition. This leads to the following null hypothesis H_0:

$$H_0 : p \sim N(0, ?_p^2) \qquad (3)$$

where $N(0, ?_p^2)$ is a normal distribution with a standard deviation of $?_p$. The standard deviation $?_p$ is derived from the individual standard deviations of the sensor error PDFs, errors due to vegetation, and specified error characteristic of the DEM.

When a fault in the form of a bias-error occurs, the PDF of the absolute disparity will contain a bias component also. Hence, the following expression for an alternative hypothesis H_1:

$$H_1 : p \sim N(?_B, ?_p^2) \qquad (4)$$

where $?_B$. is the bias-error or fault. Alternative hypotheses can be generated based on other expected error classes or faults. However, this discussion will be restricted to the analysis of bias-like errors (or faults). Under H_0, the PDF of *T* is found to be a chi-square distribution with *N* degrees of freedom. Under H_1, the PDF of *T* is found to be a non-central chi-square distribution with *N* degrees of freedom and non-centrality parameter ? [9].

SVS system requirements must specify a probability of detection under fault-free conditions, P_{FFD}, a probability of missed detection, P_{MD}, and the integration time *N*. Fault-free conditions are those conditions in which errors behave only as expected (or as specified for either the sensor or the DEM). Given the value for P_{FFD}, a threshold can be calculated from H_0 [9]. For the real-time integrity monitor used during the flight-tests, an integration time of 50 seconds (N=50) and a $P_{FFD}=10^{-4}$ were chosen. These parameter values result in a threshold value of $T_D = 96$. The probability of missed detection, P_{MD}, or a continuation of operation under the alternative hypothesis, results in a minimum detectable bias (MDB): that bias for which the probability of a missed detection is equal to P_{MD}. For example, for $P_{MD}=10^{-7}$ a MDB value of 33.96 meters results. Note that this value is quite significant.

Given the accuracies specified in [8], values for $?_p$ can be computed. Table 2 gives an overview of the values for various combinations of DGPS and DEMs. Note that this table includes $?_p$ values obtained when using DTED as well as the Shuttle Radar Topography Mission (SRTM)-derived elevation database.

	DTED 0 / KGPS	DTED 1 / KGPS	SRTM / KGPS	DTED 0 / LAAS	DTED 1 / LAAS	SRTM / LAAS	DTED 0 / WAAS	DTED 1 / WAAS	SRTM / WAAS
?$_p$	18.86	18.86	10.89	18.87	18.87	10.91	18.92	18.92	10.99

Table 2. Standard deviation of the absolute disparity under fault-free conditions.

2.2 Integrity monitoring based on forward-looking sensor technology

Integrity algorithms based on forward looking sensors statistically assess the similarity between terrain features observed by forward looking sensors and the terrain features derived from the terrain elevation database. This is illustrated in figure 2. Features may include the terrain elevation itself, but can also be derived from the elevation samples. Examples include terrain gradients and Laplacians, ridges, peaks, pits [10], and drainage networks [11].

FWL sensors have been used for a wide variety of applications such as air-to-ground ranging, terrain following [6], terrain avoidance [12,13,14], ground mapping, and have even be proposed to be used in precision approach and landing systems such as the Autonomous Precision Approach and Landing System (APALS) [15]. The latter utilizes a modified weather radar in combination with GPS and an Inertial Measurement Unit (IMU) to enable precision approach. It is important to note that APALS was designed to enable position “fixing” in support of autonomous navigation, not as an integrity monitor for a display suite such as SVS.

Figure 2 illustrates the FWL integrity monitor; A FWL sensor senses or measures the terrain ahead of the airplane. The data from the sensor is then input to a feature extraction process that detects and extracts the statistically significant features. Parallel to the sensing process, features are derived from the DEM. The main processor will then match and compare the features derived from the sensors and DEM and assess the consistency between these features in a statistical manner. If there is not enough agreement between both feature vectors an alarm must be generated and presented to the pilot in some fashion.

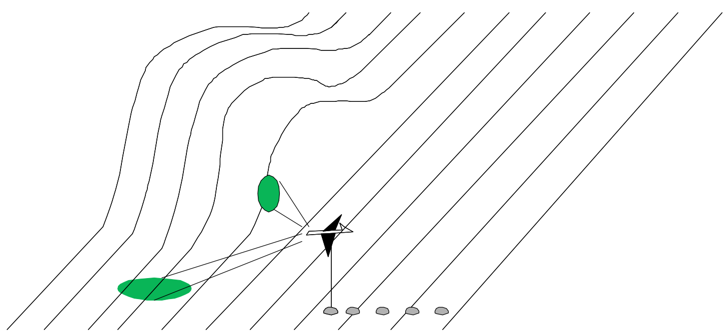

Figure 2. Forward-looking (FWL) sensor based integrity monitor

The FWL sensor candidates are divided into two groups: (1) sensors that make observations in an area ahead of the airplane; (2) sensors that make observations measurements along a straight or curved line ahead of the airplane. Examples of the former are the weather radar, millimeter-wave radar, and Light Detection and Ranging (LIDAR) sensor, whereas examples of the latter are laser range finders and FWL radar altimeters [14].

2.3 FWL versus DWL integrity monitoring

The main limitation of the DWL integrity monitor is that is does not actually “see” the terrain in front of the airplane and therfore can not make a very good assessment of the quality of the DEM ahead of the airplane. However, the DWL integrity monitor is able to build up confidence in the DEM in a statistically straightforward manner that requires a minimum retrofit to existing aircraft. The FWL integrity monitor is able to “see” ahead and can therefore make a very fast assessment of the quality of the “terrain-to-come”. However, the method is statistically complex because it not only requires the determination of the error behavior of the FWL sensor, but also uses multi-variate statistics, area mapping, and time-consuming transformations between features. Furthermore, FWL-based integrity monitoring requires either installation or modification of sensors on-board aircraft.

Choice between a FWL or DWL integrity monitor must be based on the required probability of false alarm (fault-free detection), probability of missed detection, and time-to-alarm. There may be operations in which a combination of FWL and DWL integrity monitoring must be applied to achieve the desired levels of integrity and time-to-alarm.

3. Flight test setup and results

Data from three flight tests was used to evaluate the integrity monitor's behavior as a function of various DEMs and sensor packages; two flight tests in the vicinity of Asheville (AVL), NC and one in the vicinity of Ohio University in Athens, OH (UNI). The first test was performed by the NASA Langley Research Center using an Air Force Convair aircraft known as the Total In-Flight Simulator (TIFS) operated by Veridian Engineering. The second and third flight tests were flown using Ohio University's DC-3 equipped with a real-time synthetic vision prototype with DWL integrity monitor. The core SVS system components are a Commercial-Off-The-Shelf (COTS) Honeywell Inertial Navigation System (INS) to provide the aircraft attitude, heading, and airspeed information, a prototype aircraft LAAS unit to provide the airborne position and altitude above mean sea level, a COTS Honeywell radar altimeter, a central processing unit (CPU), and a flat panel liquid crystal display that functions as HDD. The HDD software was developed by Delft University of Technology and is used through a memorandum of agreement.

The CPU runs the real-time Integrity Monitor software under the QNX real-time operating system (RTOS). The CPU computes the absolute disparities and test statistic from the input sensors. Based on the computed test statistic and the integrity threshold T_D, which has been computed *a priori*, the CPU determines if there is an integrity violation and sets an output flag accordingly. The CPU furthermore generates the information required by the HDD and sends it via a TCP/IP connection to the dedicated HDD computer.

3.1 AVL 1 Flight test results

The proposed DWL integrity monitor test statistics were calculated for a number of flight segments flown in October 1999 with the TIFS. The set of flight segments include several Instrument Landing System (ILS) approaches to runway 16 and 34. The ILS approach to runway 34 shows a different terrain profile than the approach to runway 16. During the initial approach to runway 34 the terrain is characterized by large variations (high value for ? $_T$), but during final approach the terrain variations become significantly smaller (lower value for ? $_T$). During the approach to runway 16, the frequency of undulations in the terrain remains significant until the aircraft reaches the runway.

Figure 4 shows the absolute disparity for the approaches to runway 34 and 16, respectively. Significant biases show up in the absolute disparities. When causing an alert such a bias would be blamed on the terrain elevation database. However, during this test un-modeled radar altimeter errors that are a function of the terrain roughness were expected to cause this bias [7]. Two solutions to this problem are to either incorporate the inflated radar altimeter error in the computation of ? $_p$, or find a method to more accurately determine the range to the terrain below the aircraft given the radar altimeter measurements and airplane attitude [7].

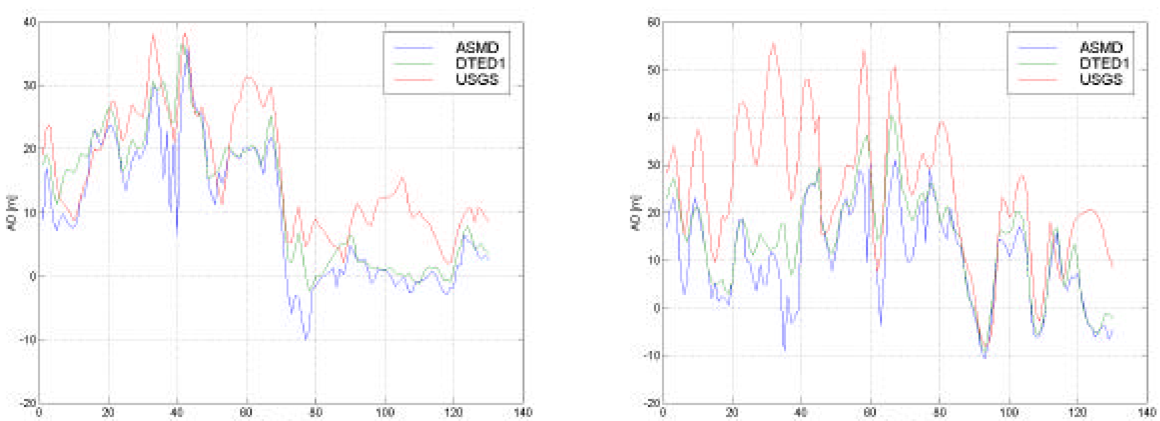

Figure 4. Absolute Disparities (AD) approaching Runway 16 (left) and 34 (right) (10/11/99 75047-75176).

Another effect to be noted in figure 4 is the difference between the absolute disparities computed using the ASM and DTED level 1 and the absolute disparities computed using the USGS. The fact that the ASM was derived from DTED level 1 explains this discrepancy. It will be necessary to investigate the difference between DTED and USGS more closely. Different vertical datums and the use of different sources (remote sensing, photogrammetry, etc.) to derive terrain elevation information is the most likely explanation.

Figure 5 shows the tests statistics for all the approaches to runways 16 and 34. The un-modeled sensor errors caused *T* to exceed the threshold on various occasions during the approach to runway 16.

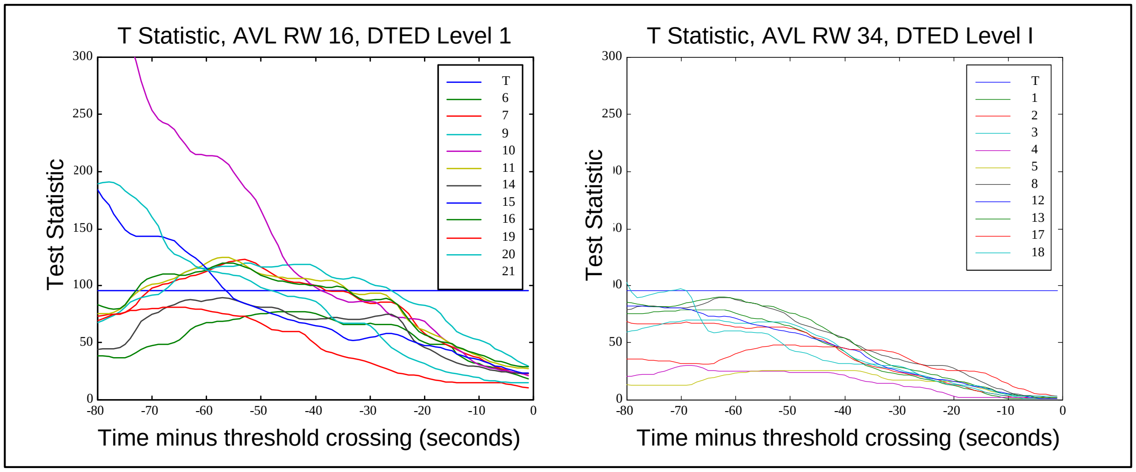

Figure 5. T statistics for the approach to runways 16 and 34, N=50, KGPS

3.2 UNI Flight test results

The second data set was collected during a flight test with Ohio University's DC-3 in the vicinity of Ohio University airport (UNI) in August 2000. The data shown here was derived in post-flight to enable a direct performance comparison between the integrity monitor's performance with LAAS / KGPS and DTED level 0 / DTED level 1. Figure 6 shows the ground-tracks for the 14 approaches (2 to runway number 7, 12 to runway number 25). Note the curvature of the approaches to runway number 7. The resultant bank angles introduce errors due to the measurement mechanism of the radar altimeter [7].

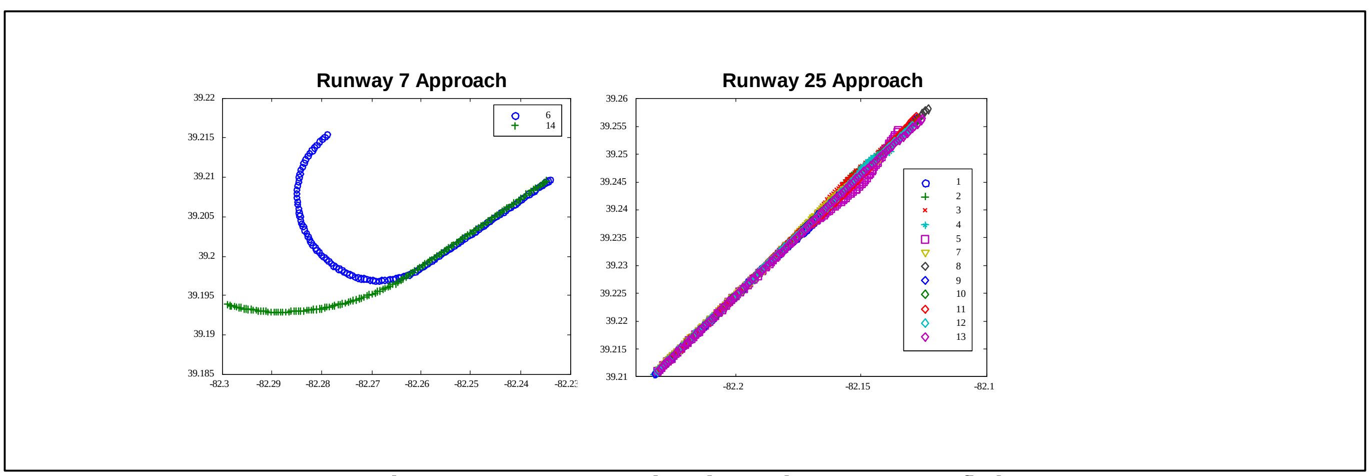

Figure 6. Approaches to UNI runway 7 and 25 during the August 2000 flight test.

The *T*-statistic results for the approaches towards runway 7 and 25 are shown in Figures 7 and 8, respectively. The graph on the left shows the monitor's behavior when utilizing DTED level 0, whereas the graph on the right shows the monitor’s behavior when utilizing DTED Level 1. One can observe an obvious difference in integrity monitor performance: using DTED level 0 causes the integrity threshold to be exceeded. In other words the interpolation error introduced by the large spatial resolution of DTED level 0 causes the actual fault-free error characteristic to deviate from the specified fault-free error characteristic. This will then result in the occurrence of false alarms.

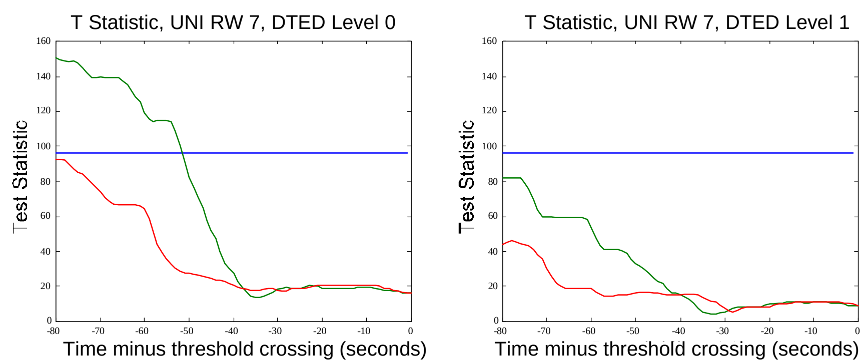

Figure 7. T-statistic and threshold for the approach to UNI runway 7 utilizing DTED level 0 and 1

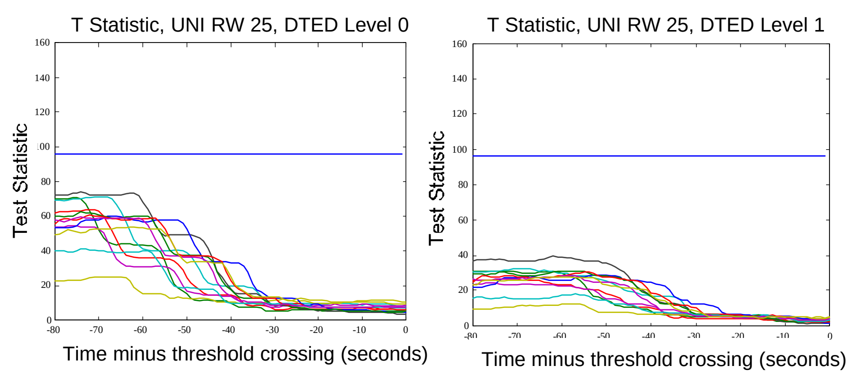

Figure 8. T-statistic and threshold for the approach to UNI runway 25 utilizing DTED level 0 and 1.

Furthermore, it can be seen in figure 7 that the test statistics during the approaches to runway 7 are much larger than the test statistics during the approaches to runway 25. The reason for this is error is twofold: first the terrain underneath the approach to runway 7 has a higher terrain standard deviation than the terrain underneath the approach to runway 25 and secondly, the large bank angles cause a mismatch between the radar altimeter measurements and the interpolated DEM elevation.

3.3 AVL 2 Flight test results

Flight tests were performed in the vicinity of the Asheville, NC, airport (AVL) in September 2000. Figure 9 shows the ground tracks for these approaches. The proposed test statistics were calculated for the 14 flight segments flown. The set of flight segments consisted of Instrument Landing System (ILS) approaches to runway 16 and 34. The test statistics for these approaches are given in figures 10 and 11, respectively.

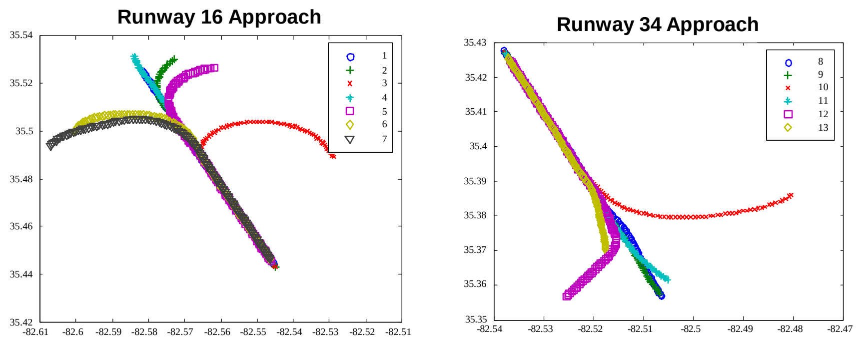

Figure 9. Ground-tracks for the approaches to runway 16 and runway 34 at AVL

Again, when using DTED level 1, no integrity violations were detected. However, when using DTED level 0, the thresholds are exceeded for approaches to both runways. Again, interpolation errors due to a limited spatial resolution are the cause of these false alarms. In [16] the AVL DTED segment was compared to high-accuracy photogrammetry data and no faults were identified.

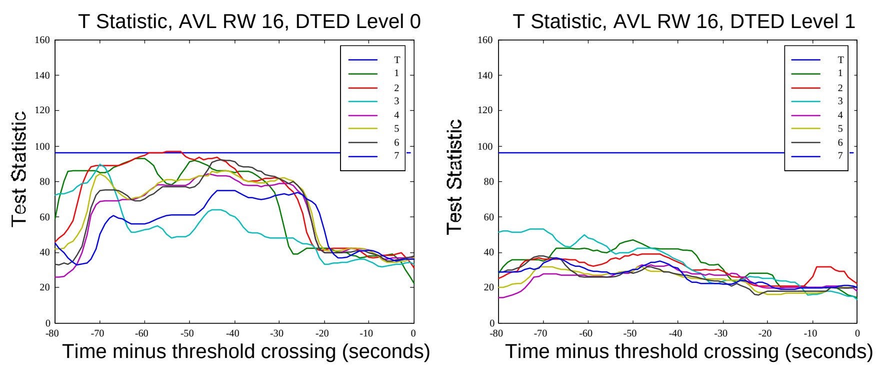

Figure 10. T-statistic and threshold for the approach to AVL runway 16 utilizing DTED level 0 and 1.

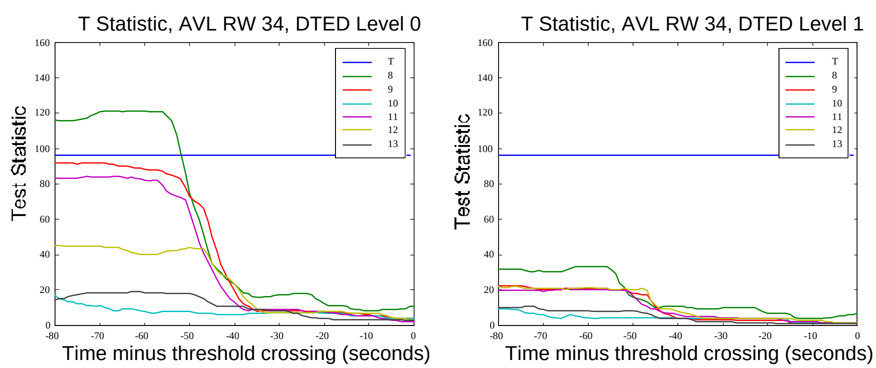

Figure 11. T-statistic and threshold for the approach to AVL runway 34 utilizing DTED level 0 and 1.

The data shown in figures 10 and 11 was generated using LAAS positions and altitudes. A very similar integrity monitor performance is found when using post-flight KPGS. This is to be expected because the standard deviation of the PDF of the absolute disparity is dominated by the vertical standard deviation of the DEM.

Conclusions

SVS may require a DEM integrity monitor to guarantee integrity levels higher than required for advisory systems. Integrity monitors can be based on downward looking (DWL) sensor information, forward looking (FWL) sensor information or both DWL and FWL sensor information. Integrity monitors based on DWL sensors can be derived in a statistically straightforward manner and require minimal retrofit of existing aircraft, whereas integrity monitors based on FWL sensors are statistically more complex and may require installation or modification of sensors on board aircraft. However, FWL-based sensors enable DEM integrity monitoring of “terrain-to-come”. Although methods based on DWL sensors are estimated to be sufficient for most applications FWL schemes may be necessary to guarantee DEM integrity for safe SVS flight procedures during all operational scenarios.

Two flight tests in the vicinity of Asheville, NC and one in the vicinity of Ohio University in Athens, OH were used to evaluate DWL integrity monitor behavior as a function of various DEMs and sensor packages. The test statistic values for both geographic areas were consistent and below the threshold for all approaches using DTED level 1. Use of DTED level 0 in the real-time integrity monitor caused the integrity threshold to be exceeded on various occasions. It is concluded that the limited spatial resolution of DTED level 0 causes an interpolation error that was not included in the nominal error characteristic. This off-nominal behavior resulted in false alarms and possibly missed detections. DTED level 1 was shown to be sufficient. However, degraded performance of DGPS or radar altimeter may necessitate even higher quality terrain databases. Comparing the results of both Asheville flight tests indicates a discrepancy in integrity monitor performance for same-runway approaches. This can be attributed to the use of different radar altimeters in both test aircraft. Additional flight-tests using a variety of radar altimeters will be necessary to validate the general performance of the DEM integrity monitor.

Though the integrity monitor performance looks promising, it is highly recommended that it’s true system performance be adequately studied, using techniques such as failure mode effect analysis techniques. During this time, research would include assurance that MDB’s are also acceptable and observable.

References

1. **Williams, D., et al.**, “Concept of Operations for Commercial and Business Aircraft Synthetic Vision Systems – Version 1.0,” NASA Langley Research Center, January 2001.
2. "Terrain Awareness and Warning Systems", Federal Register - Rules and Regulations, FR Doc 00-7595, Vol. 65, No. 61, pp. 16735-16756, March 27, 2000.
3. **Etherington, T. J., et al**., “Synthetic Vision Information System,” Proceedings of the Digital Avionics Systems Conference, Philadelphia, 7-13 October 2000.
4. **Hinrichs, P.R**., “Advanced Terrain Correlation Techniques,” IEEE PLANS, San Diego, CA, 1989, pp. 89-96
5. **Baird, C. A.** and **M. R. Abramson**, “A Comparison of Several Digital Map-Aided Navigation techniques,” IEEE PLANS, 1984, pp. 286-293.
6. **Siouris, G. M**., *Aerospace Avionics Systems – A Modern Synthesis*, Academic Press, Inc., 1993.
7. **Uijt de Haag, M.**, **J. Campbell**, **R. Gray**, “A Terrain Database Integrity Monitor for Synthetic Vision Systems,” Proceedings of the Digital Avionics Systems Conference, Philadelphia, 7-13 October 2000.
8. **Gray, R. A**., “In-flight Detection of Errors for Enhanced Aircraft Flight Safety and Vertical Accuracy Improvement Using Digital Terrain Elevation Data with an Inertial Navigation System, Global Positioning System and Radar Altimeter,” Ph.D. Dissertation, Ohio University, Athens, Ohio, June 1999.
9. **Uijt de Haag, M**. et al., “Flight Test Results of a Synthetic Vision Elevation Database Integrity Monitor,” Proceedings of the Society of Photo-Optical Instrumentation Engineers (SPIE), Orlando, FL, Apr. 16, 2001.
10. **Kweon, I. S., and Takeo Kanada**, “Extracting Topographic Features for Outdoor Mobile Robots,” Proceeding of the 1991 IEEE International conference on robotics and automation, Sacramento, CA.
11. **Bennett, D. A., and M. P. Armstrong**, “An Inductive Knowledge-Based Aproach to Terrain Feature Extraction,”, Cartography and Geographic Information Systems, Vol. 23, No. 1, 1996.
12. **Kayton, M. and W. R. Fried**, *Avionics Navigation Systems*, Second Edition, John Wiley & Sons, 1997
13. **Ammar, D. F. et al.**, “Radar Based Terrain and Obstacle Alerting System,” U.S. Patent, Patent Number 5,945,926, August 31, 1999.
14. **Becker R. C. and L. D. Almstedt**, “Flight Test Evaluation of a 35GHz Forward Looking Altimeter for Terrain Avoidance,” IEEE AES Systems Magazine, February 1995.
15. **Dieffenbach, O.**, “APALS™ Autonomous Precision Approach and Landing System,” Proceedings of the Society of Photo-Optical Instrumentation Engineers (SPIE), Orlando, FL, Apr. 18, 19, 1995.
16. **Uijt de Haag, M, J. Sayre, and J. Campbell**, “A DTED Terrain Avoidance System using GPS and Radar Altimeter Monitoring,” Ohio University Preliminary Design Review at NASA Langley, November 28, 2000.